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Early-type Stars: Most Favorable Targets for Astrometrically Detectable Planets in the Habitable Zone

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ABSTRACT

Early-type stars appear to be a difficult place to look for planets astrometrically. First, they are relatively heavy, and for fixed planetary mass the astrometric signal falls inversely as the stellar mass. Second, they are relatively rare (and so tend to be more distant), and for fixed orbital separation the astrometric signal falls inversely as the distance. Nevertheless, because early-type stars are relatively more luminous, their habitable zones are at larger semi-major axis. Since astrometric signal scales directly as orbital size, this gives early-type stars a strong advantage, which more than compensates for the other two factors. Using the Hipparcos catalog, we show that early-type stars constitute the majority of viable targets for astrometric searches for planets in the habitable zone. We contrast this characteristic to transit searches, which are primarily sensitive to habitable planets around late-type stars.

Subject headings: astrobiology – astrometry – stars: early-type – planetary systems – extraterrestrial intelligence

1. Introduction

To date, extrasolar planets have been discovered by three methods: pulsar timing (Wolszczan 1994), radial velocities (RV, Mayor & Queloz 1995), and transits (Udalski 2002; Konacki et al. 2003). While RV has been by far the most successful of these (Butler et al. 2002), it appears to be ultimately limited to $1\,\mathrm{m\,s^{-1}}$ precision by instabilities in the atmospheres of stars. For planets in $a \sim 1\,\mathrm{AU}$ orbits around solar-type stars, this corresponds to a planetary mass $m_p \sim 10\,M_\oplus$. Hence, to find terrestrial planets will probably require other techniques.

Of particular interest are terrestrial planets in the so-called "habitable zone". While the exact specifications of this concept are the subject of continuing study and debate, for purposes of this paper, we will assume the habitable zone to be centered at

$$a_{\rm habit} = 1\,{\rm AU}\sqrt{\frac{L}{L_\odot}}, \tag{1}$$

where L is the bolometric luminosity of the star.

A quick survey of various techniques reveals four with reasonable potential for detecting terrestrial planets: pulsar timing, microlensing (Mao & Paczyński 1991), transits, and astrometry (Shao 1996). However, only two of these, transits and astrometry, show reasonable prospects of detecting habitable planets. Pulsar timing has already found three terrestrial planets in one system, but the intense radiation field from the pulsar makes these almost certainly uninhabitable. Microlensing is probably the most efficient method for detecting Earth mass (and even sub-Earth mass) planets (Bennett & Rhie 2002). However, it is sensitive primarily to planet-star separations of an Einstein ring (Gould & Loeb 1992), which is roughly at $a \sim 4\,{\rm AU}(M/M_\odot)^{1/2}$, where M is the mass of the star. This is well outside the habitable zone.

Detection of terrestrial planets, including in the habitable zone, is the primary goal of three proposed space missions: *Kepler*[1] and *Eddington*[2] plan to search for these by planetary transits, while the *Space Interferometry Mission (SIM)*[3] plans to search for them from the astrometric wobble they induce on their parent star.

Gould, Pepper & DePoy (2002) showed that the transit technique is actually most sensitive to habitable planets orbiting low-mass stars because their low luminosity moves the habitable zone inward (see eq. [1]) where transits are most efficiently detected. This factor, together with the greater abundance and smaller radii of low-mass stars, more than compensate for the worse signal-to-noise ratio (S/N) due to their lower brightness. Here we ask whether the particularities of the astrometry also influence which stellar population this technique is most sensitive to when searching for habitable planets.

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[1]http://www.kepler.arc.nasa.gov/

[2]http://sci.esa.int/home/eddington/index.cfm

[3]http://planetquest.jpl.nasa.gov/SIM/sim_index.html

2. Analytic Investigation

Consider a homogeneous population of stars of mass M, bolometric luminosity L, and space density n. Assume that astrometric wobbles of amplitude $\alpha_{\rm min}$ can be reliably detected. A planet of mass m_p in the habitable zone (as defined by eq. [1]), can then be detected out to a distance $d = (m_p/M)(L/L_\odot)^{1/2}({\rm AU}/\alpha_{\rm min})$. Hence, the total number of systems that can be probed is,

$$N = \frac{4\pi}{3}n\left(\frac{m_p}{M}\right)^3\left(\frac{L}{L_\odot}\right)^{3/2}\left(\frac{\alpha_{\rm min}}{\rm AU}\right)^3$$
$$= 7.6\,\frac{n}{n_0}\left(\frac{m_p}{3\,M_\oplus}\right)^3\left(\frac{M}{M_\odot}\right)^{-3}\left(\frac{L}{L_\odot}\right)^{3/2}\left(\frac{\alpha_{\rm min}}{1\,\mu{\rm as}}\right)^{-3}, \qquad (2)$$

where we have normalized the density to $n_0 = 2.5\times 10^{-3}\,{\rm pc}^{-3}$, the space density per M_V-magnitude of solar-type stars. The key point to note is that, in the neighborhood of $M \sim 1\,M_\odot$, the bolometric luminosity scales as $L \propto M^\beta$, where $\beta \sim 4.5$. Hence the mass and luminosity terms can be combined to yield

$$N \propto nM^{1.5\beta-3} \sim nM^{3.75}. \qquad (3)$$

Although the number density of stars falls rapidly as a function of mass, both because fewer are formed and those that do form live shorter lives, this is somewhat compensated by the fact that these younger stars have a lower scaleheight $h(M)$ and so are more concentrated near the plane. The shorter lifetime scales as $t \propto M/L$, but this is relevant only for stars $M \gtrsim M_\odot$, whose lifetimes are shorter than the age of the Galactic disk. The falling mass function scales as $dn/d\ln M \propto M^{-x}$, where $x = 1.35$ is the Salpeter value. These factors can be combined to obtain,

$$\frac{dN}{d\ln M} \propto \frac{M^{\beta/2-x-2}}{h(M)} \sim \frac{M^{-1.1}}{h(M)} \qquad M \gtrsim M_\odot \qquad (4)$$

and,

$$\frac{dN}{d\ln M} \propto M^{1.5\beta-x-3} \sim M^{2.4} \qquad M \lesssim M_\odot \qquad (5)$$

Since the scaleheight factor in equation (4) tends to counter the mass factor, one expects that astrometric sensitivity will peak at $M \sim M_\odot$ and then be roughly flat toward higher masses.

3. Numerical Evaluation

To obtain more definite estimates, we determine the minimum mass that can be detected for each star in the Hipparcos catalog (ESA 1997), assuming that each has a planet with semi-major axis as given by equation (1). We determine M_V using the Johnson V mag and parallax as given by the Hipparcos catalog, and we find the bolometric corrections by making use of the catalog's $V-I$ colors. We estimate the mass using M_V and the mass-luminosity relation of Cox (1976). We adopt $\alpha_{\rm min} = 1\,\mu$as, which is the current best estimate for $5\,\sigma$ detections for a 5-year *SIM* mission (M. Shao 2002, private communication). It corresponds to 50 measurements, each with $1\,\mu$as precision for face-on orbits or 100 measurements for edge-on orbits. We also allow that this performance will be a weak function of apparent magnitude, $\alpha_{\rm min} = (1 + 10^{0.4(11-V)})^{1/2}\,\mu$as, which has the correct form in both the systematics-limited and photon-limited regimes. However, including the flux-dependent term has hardly any effect on the results. In addition, we arbitrarily assign all red giants (defined as $M_V < 4$ and $V - I > 0.7$) a mass $M = 1.00\,M_\odot$. Red-giant masses are difficult to estimate, but this estimate is not likely to be far off in most cases. In addition, fixing the red-giant masses at a unique value makes them easy to identify in Figure 1, which displays our results.

Planets with periods $P < 5\,$yr are shown by crosses, those with $P > 10\,$yr are shown by solid squares, and those in between by open circles. However, the red giants ($M \equiv 1\,M_\odot$) with $P > 10\,$yr (of which there are 401) are not shown to avoid clutter. These period distinctions are important because at the $5\,\sigma$ S/N limit used here, planets cannot be reliably detected in less than one orbit.

Restricting consideration to planets with periods $P < 5\,$yr, there are 36 stars that can be probed with $M < M_\odot$ and 47 with $M > M_\odot$. In addition, there are 9 red giants. Some consideration is being given to extending the *SIM* mission from 5 to 10 years[4]. For this case, the respective numbers are 36, 62, and 25. In either case, the early-type stars dominate over the late-type.

4. Discussion

The sensitivity of astrometric surveys to habitable planets around early-type stars makes them complementary to transit surveys. If these are properly executed (Gould, Pepper & DePoy 2002), they will be sensitive primarily to habitable planets around late-type stars. See Figure 2.

While early-type stars may have planets in the habitable zone, that does not necessarily mean that these can be inhabited by natural processes. On Earth, almost a Gyr was required

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[4]The main reasons for an extended mission would be to push the sensitivity to lower masses by increasing the S/N as well as to find longer-period planets. For clarity, however, in Figure 1 we use the same $1\,\mu$as precision based on a 5-year mission for all stars regardless of period.

before life took hold, and several more were required before it succeeded in radically transforming the atmosphere. Very early stars do not live long enough to permit this leisurely development. However, there are a large number of targets with masses $M \lesssim 1.5\,M_\odot$, and these can live for $\gtrsim 2.5\,\mathrm{Gyr}$. Moreover, it may be that life elsewhere in the universe develops faster than on Earth. Targeting these early-type stars for habitable-planet searches is the best way to find out.

The time that red giants spend at approximately their current luminosity (and so that a planet at a given semi-major axis would remain in the habitable zone) is even shorter than the lifetime of many early-type stars. This would appear to give even less time for life to develop. However, if these stars had harbored planets in the habitable zone during their main-sequence phase, and if these planets gave rise to intelligent, technologically advanced life, these beings could have moved their home to progressively greater semi-major axes by orchestrating suitable interactions with an asteroid or comet, in order to maintain their planet's habitability as their star aged (Korycansky, Laughlin, & Adams 2001).

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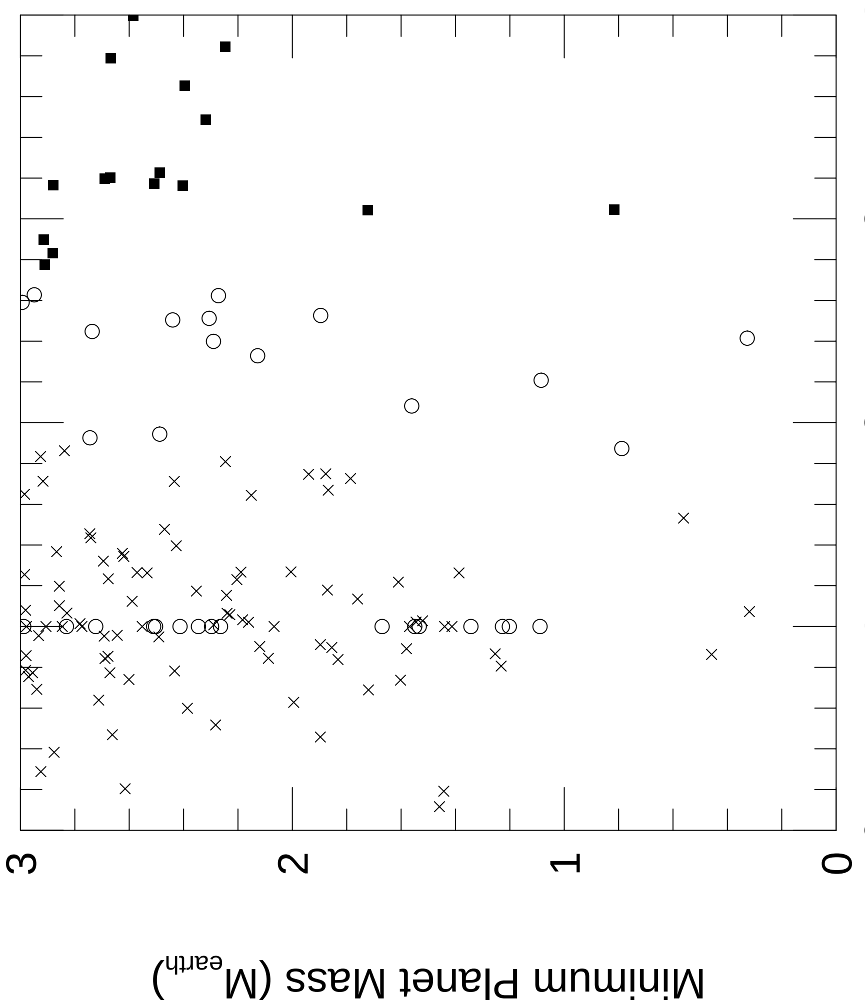

Fig. 1.— Minimum mass of detectable planets in the habitable zone as a function of stellar mass for stars in the solar neighborhood taken from the Hipparcos catalog (ESA 1997). Planets with periods $P < 5\,\mathrm{yr}$ (*crosses*), $5\,\mathrm{yr} < P < 10\,\mathrm{yr}$ (*open circles*), and $P > 10\,\mathrm{yr}$ (*solid squares*), are shown separately. Red giants are all assigned a mass $M = 1\,M_\odot$, but the $P > 10\,\mathrm{yr}$ giants are not shown to avoid clutter. For $P < 5\,\mathrm{yr}$, stars with $M > M_\odot$ outnumber those with $M < M_\odot$ by 47 to 36, while for $P < 10\,\mathrm{yr}$ the ratio is 62 to 36.

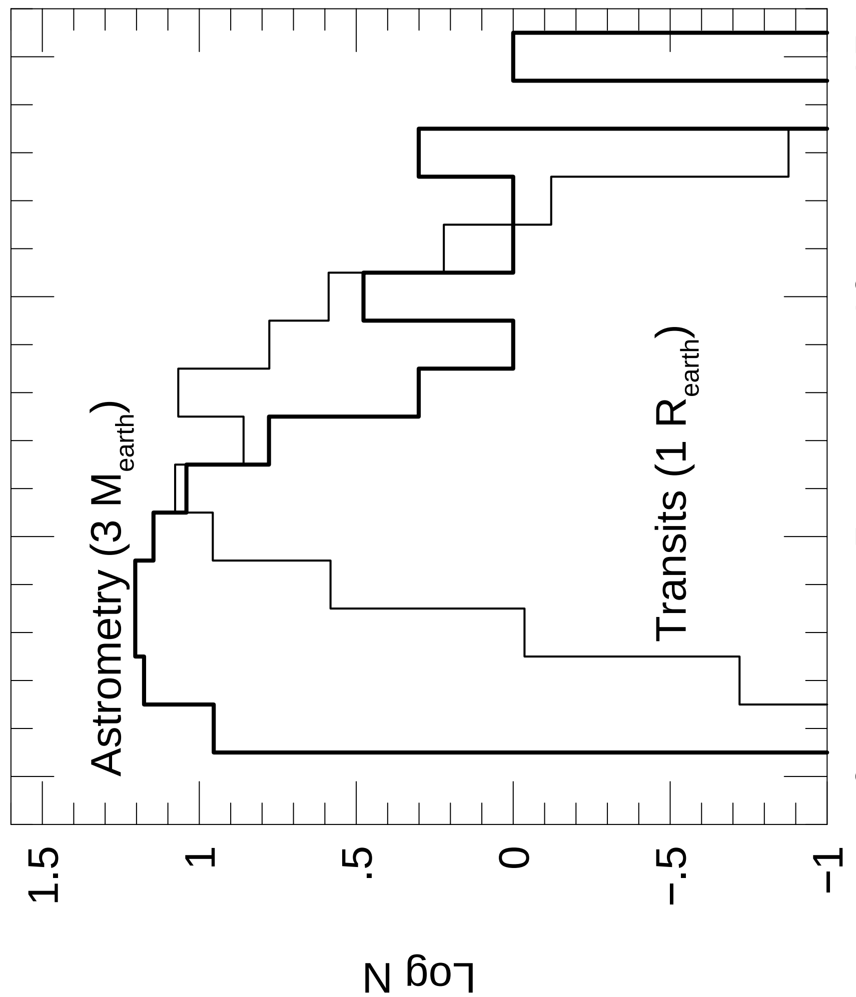

Fig. 2.— Histograms of sensitivities of astrometric and transit surveys to planets in the habitable zone. The astrometric curve shows the same stars as in Fig. 1, excluding all red giants and all stars with $P > 10\,\mathrm{yr}$. The transit curve is taken from Gould, Pepper & DePoy (2002), who adopted the characteristics of the *Kepler* mission, but (contrary to the *Kepler* website) assumed that faint late-type dwarfs would be included in the survey. Since astrometric surveys are sensitive to mass, while transit surveys are sensitive to radius, the two curves are not strictly comparable, but the relative trends with stellar type are robust.